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 K^- -proton scattering and the $\Lambda(1405)$ in dense matter

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The scattering of antikaons with nucleons is studied in the nuclear environment. Describing the $\Lambda(1405)$ as a K^- proton bound state, we find, that due to the Pauli blocking of intermediate states, the mass of the $\Lambda(1405)$ is shifted upwards in energy, above the K^- proton threshold and its width is somewhat broadened. As a consequence the s-wave K^- -nucleon scattering length turns attractive at finite nucleon density ($\rho \geq 0.25\rho_0$) leading to a mean field potential for the K^- of about ~ -100 MeV in nuclear matter at ground state density. Consequences for Heavy Ion collisions and possible experimental checks for the structure of the $\Lambda(1405)$ are discussed

1 Introduction

Recently the physics of kaon-nucleon scattering has received considerable interest because of possible implications for the structure of neutron stars and relativistic heavy ion collisions. First speculations about the possibility of kaon condensation have been put forward by Kaplan and Nelson [1] and Politzer and Wise [2] on the basis of a simple mean field evaluation of a Lagrangian derived from chiral perturbation theory. At mean field level this Lagrangian predicts two potentials for the kaons. (i) A scalar term due to explicit chiral symmetry breaking, which is attractive for both K^+ and K^- , and which involves the kaon-nucleon-sigma term. (ii) A vector term due to vector meson (ρ , ω) exchange, which is attractive for the K^- and repulsive for the K^+ . For the K^+ these two terms essentially cancel each other leading to a small repulsive potential for the K^+ . For the K^- , on the other hand, scalar and vector term add up to a large attractive mean field potential which, depending on the choice of the sigma-term, leads to a critical density of $2 - 5 \rho_0$ for kaon condensation, where ρ_0 is the nuclear matter ground state density. Based on this model for the K^- mean field Brown et al. [3] found that the nuclear equation of state softens considerably resulting in qualitatively new properties of neutron stars and leading to the speculation of Brown and Bethe [4] about the existence of small mass black holes. Rho and collaborators [5], furthermore, have carried the work of Kaplan and Nelson to higher order in the chiral counting but did not find qualitatively new features. In heavy ion physics, the mean fields would help to explain the observed slope difference between K^+ and K^- spectra at AGS energies (14 GeV/u) [6] as well as the production of subthreshold K^+ at SIS energies (~ 1 GeV/u) [7].

There is, however, a phenomenological problem with the approach of Kaplan and Nelson. It is well known that s-wave the K^- nucleon scattering length is repulsive at threshold [8] ($a_{K-N} = -.15$ fm). Therefore, at very low densities, where the impulse approximation should be valid, we would expect a repulsive mean field of the form $U \sim -4\pi a_{K-N}\rho$. Kaplan and Nelson on the other hand would predict an attractive K^- nucleus optical potential even at arbitrarily low density, which is equivalent to say, that their scattering amplitude obtained at tree level does not agree with experiment. The reason for this disagreement is the existence of the s-wave, isospin $I = 0$ $\Lambda(1405)$ resonance in the K^- proton-channel just below threshold. Scattering through this resonance, which can be understood as a K^-p bound state in the continuum [9, 10], gives rise to a repulsive contribution to the scattering amplitude at threshold. This phenomenon is well known in nuclear physics: the p-n scattering length in the deuteron channel ($I = 0, S = 1$) is repulsive due to the existence of the deuteron as a bound state¹.

The mean field potential of Kaplan and Nelson simply ignores the existence of the

¹Actually simple arguments from low energy scattering show, that the existence of a bound state below threshold always leads to a repulsive scattering length [11].

$\Lambda(1405)$ resonance and, therefore, gives the wrong low density behavior for the s-wave K^- -nucleus optical potential. The question then, of course, is to which extent this model can be trusted at higher densities. In a recent work Lee et al. [5] have included an explicit resonance term for the $\Lambda(1405)$ in their calculation of the K-N scattering amplitude in chiral perturbation theory. After adjusting the counter terms, they conclude that the existence of the $\Lambda(1405)$ does not affect the conclusions about the existence of the K^- -condensate, because the kaon-wave in the condensate is very much off shell, below the $\Lambda(1405)$ resonance. While this reasoning may be in principle correct, it of course relies heavily on the off shell properties of the $K^- - p$ amplitude. The use of mean field potentials, of course, would be justified much better, if the $\Lambda(1405)$ would not exist at all in dense matter. This is the case in our example of the deuteron. There, we know, that nuclei are not made out of deuterons, and that the mean field approximation works very well. The reason is that the Pauli principle destroys the deuteron in the nuclear environment. Proton and neutron cannot form a bound state, because the momentum space their wave function would occupy is already occupied by other nucleons in the environment. In more technical terms, the intermediate states of the p-n t-matrix are Pauli blocked in matter such that no pole below threshold is formed. Consequently, if the $\Lambda(1405)$ can be understood as a $K^- - p$ bound state, similar effects due to Pauli blocking should change its properties in the nuclear medium.

It is the purpose of this article to quantitatively investigate, how the nuclear environment changes the properties of the $\Lambda(1405)$ and what the consequences for the in medium properties of the K^- are. This investigation naturally relies on the assumption that the $\Lambda(1405)$ is indeed a $K^- - p$ bound state and not a genuine 3-quark state. Therefore, all changes we predict due to the effect of Pauli blocking of the proton in nuclear medium are absent if the $\Lambda(1405)$ is a genuine 3-quark state. Consequently, the medium effects discussed here, can be used to *experimentally* distinguish between the two pictures for the $\Lambda(1405)$. As we will show below, for densities $\rho \leq \rho_0$ the effect of the medium is to move the position of the $\Lambda(1405)$ up in energy, while its width remains essentially constant. This behavior can be observed in experiment by photo production of the $\Lambda(1405)$ in a nucleus via the reaction

$$\gamma + p \rightarrow K^+ + \Lambda(1405) \quad (1)$$

We estimate, that this experiment should be feasible at CEBAF energies.

This article is organized as follows. In the next section we will briefly discuss the phenomenology of the K^-p scattering and introduce the model which we will use to describe the $\Lambda(1405)$. Section 3 will be devoted to the consequences for the K^- self energy. We will briefly address the issue of finite temperature, which is relevant to the phenomenology of relativistic heavy ion collisions. Finally, in section 4 we will discuss possible experimental checks for the structure of the $\Lambda(1405)$ and implications of our

results for the physics of heavy ion collisions as well as for astrophysics.

2 The model

The idea to understand the $\Lambda(1405)$ as a K^-p - bound state is not at all new. Already back in the sixties [9] attempts have been made to describe it as a bound state in a Yukawa potential due to vector meson exchange. More recently Siegel and Weise investigated the K^- -nucleon scattering by using a separable potential model as well as a local Yukawa interaction. Although some details of the amplitude needed additional ingredients, such as explicit SU(3) breaking as well as a weakly coupling s-channel resonance slightly below threshold, the cross features of the $I = 0$ amplitude and the position of the $\Lambda(1405)$ resonance could be reproduced well with the separable potential alone. Finally, a very detailed calculation in the spirit of the Bonn-meson exchange model has been carried out by the Jülich group [12].

In this work, we want to restrict ourselves to a separable potential model for the K^-p interaction, because it can be solved algebraically in momentum space and the Pauli blocking can be incorporated easily. It also makes the effect of the Pauli blocking more transparent and certainly will provide the correct qualitative picture and a reasonable quantitative estimate of the effects to be expected from a more detailed calculation using e.g. the Jülich approach. Since the K^-N -system strongly couples to other channels, such as $\Sigma\pi$, we have to treat the full coupled channels problem.

Siegel and Weise have demonstrated that around threshold a nonrelativistic description of the K^- -nucleon system works well. We, therefore, will restrict ourselves to a nonrelativistic treatment of the problem and, hence, have to solve the following Schrödinger – type equation.

$$\nabla^2\psi_i(r) + k_i^2\psi_i(r) - 2\mu_i \int V_{i,j}(r, r') \psi_j(r') d^3r' = 0 \quad (2)$$

where $\psi_i(r)$ represents the wave function and μ_i the reduced mass for the channel i . The center of mass momenta k_i of channel i are related to the total energy E by

$$k_i^2 = \frac{[E^2 - (M_i - m_i)^2][E^2 - (M_i + m_i)^2]}{4E^2} \quad (3)$$

where m_i and M_i are the masses of meson and baryon in channel i . Since we are interested in the isospin $I = 0$ channel, only the K^-p and the $\Sigma\pi$ -channels contribute.

For the separable potential we use the following ansatz in momentum space

$$\begin{aligned} V_{i,j}(k, k') &= g^2 C_{i,j} v_i(k) v_j(k') \\ &= \frac{g^2}{\Lambda^2} C_{i,j} \Theta(\Lambda^2 - k^2) \Theta(\Lambda^2 - k'^2) \end{aligned} \quad (4)$$

Contrary to ref [10], in which a Yukawa form for $v_i(k)$ was used, we use a sharp cutoff in momentum space. As we will show, this potential is sufficient to reproduce the K^-p amplitude in the region of interest and we feel that the medium effects we are about to study become more transparent, when using this simpler potential.

The KN scattering amplitude is best studied by solving for the so called T-matrix, which is equivalent to solving the Schrödinger equation for the scattering problem (see e.g. ref. [13]). Following [13], the T-matrix is given by

$$T_{i,j}(k, k', E) = V_{i,j}(k, k') + \sum_l \int \frac{d^3q}{(2\pi)^3} V_{i,l}(k, q) \frac{1}{E - m_l - M_l - q^2/(2\mu_l)} T_{l,j}(q, k') \quad (5)$$

where the energy E is related to the eigenvalue k_i^2 of the Schrödinger equation (2) given by eq. (3). In case of a separable potential this integral equation is readily solved by

$$T_{i,j}(k, k', E) = g^2 v_i(k) v_j(k') \left[(1 - C \cdot G(E))^{-1} \cdot C \right]_{i,j} \quad (6)$$

where we have defined the ‘propagator’ matrix

$$\begin{aligned} G_{i,j} &= \text{diag}(g_i); \\ g_i(E) &= g^2 \int \frac{d^3p}{(2\pi)^3} \frac{v_i^2(p)}{E - m_i - M_i - p^2/(2\mu_i)} \\ &= \frac{1}{2\pi^2} \frac{g^2}{\Lambda^2} \int_0^\Lambda \frac{p^2 dp}{E - m_i - M_i - p^2/(2\mu_i)} \end{aligned} \quad (7)$$

Here we have inserted our choice for the potential $v(k) = \frac{\Theta(k^2 - \Lambda^2)}{\Lambda}$. The scattering amplitude is directly related to the T-matrix by [13]

$$f_{i,j}(k, k') = -\frac{\mu_i}{2\pi} T_{i,j}(k, k') \quad (8)$$

Finally, for the interaction matrix C_{ij} , we use the standard result derived from $SU(3)$ flavor symmetry (see e.g. ref [9, 10])

$$C_{i,j} = \begin{pmatrix} K^-p & \pi\Sigma \\ -\frac{3}{2} & -\frac{\sqrt{6}}{4} \\ -\frac{\sqrt{6}}{4} & -2 \end{pmatrix} \begin{matrix} K^-p \\ \pi\Sigma \end{matrix} \quad (9)$$

where it is assumed that all interactions are mediated by vector meson exchange.

Λ [GeV]	$g^2/4\pi$
1.0	1.733
0.78	1.425
0.6	1.2

Table 1: Combinations of cutoff Λ and coupling g leading to the amplitudes shown in fig. 1.

In fig. 1 we compare the results, using three different cutoffs, for the $I = 0$ K^-N forward scattering amplitude $f(\omega) = f(k = k', \omega)$ with that extracted from experimental data by Martin [8]. The agreement with the ‘data’ is reasonably good and essentially independent from the choice of the cutoff. The coupling g , of course, depends on the cutoff chosen and the values needed to reproduce the data are listed in table 1.

Having demonstrated that our model, independent from the cutoff, can reproduce the data in free space we now can proceed to finite density.

3 Finite density

In the nuclear medium, because of the Pauli blocking, the intermediate proton states with momenta $p \leq k_f$, where k_f is the fermi momentum, are forbidden. As a consequence the propagator for the K^-p intermediate state $g_1(E)$ (7) changes to

$$g_1(E, k_f) = \frac{1}{2\pi^2} \frac{g^2}{\Lambda^2} \int_{k_f}^{\Lambda} dp p^2 \frac{1}{E - m_{Kaon} - m_{proton} - p^2/(2\mu_{Kp})} \quad (10)$$

while that for the $\pi\Sigma$ remains unaffected by the nuclear environment. Of course nucleon and kaon are also subject to mean field forces, which changes their self energy in the medium. In a more consistent treatment along the line of a Brueckner Hartree-Fock scheme, both effects need to be taken into account together. This, however, is beyond the scope of this article and will be addressed in a more complete investigation.

In order to qualitatively see the effect of Pauli blocking of the intermediate states, let us ignore the coupling to the $\pi\Sigma$ -channel for a moment. In this case from eq. (7) the binding energy of the $\Lambda(1405)$ is given by the solution of the integral equation

$$1 - \frac{1}{2\pi^2} \frac{g^2}{\Lambda^2} \int_0^{\Lambda} dp p^2 \frac{\Theta(k_f - p)}{E - m_{Kaon} - m_{proton} - p^2/(2\mu_{Kp})} = 0 \quad (11)$$

The eigenvalue E obtained from this equation is plotted as a function of the nuclear density $\rho = \frac{2}{3\pi^2} k_f^3$ in fig. 2 for two different cutoffs Λ . Here the couplings g have been

readjusted such that the empirical value at $\rho = 0$ of $E = 1.405$ GeV is obtained. This readjustment is necessary since we have ignored the $\pi\Sigma$ -channel. We see that the position of the $\Lambda(1405)$ moves up in energy with increasing density and reaches the K^-p -threshold ($\omega = 0$) at $\rho \simeq 0.5\rho_0$. This behavior can be easily understood from eq. (11). The support of the integral is reduced with increasing density reflecting the truncation of momentum space due to Pauli blocking. In order to still satisfy eq. (11) the denominator in the integrand has to be reduced by increasing the energy eigenvalue E . Notice, that even if the energy eigenvalue of the $\Lambda(1405)$ turns positive, the $\Lambda(1405)$ cannot decay into a K^- and proton, since the final state for the proton is Pauli-blocked. As can be seen from eq. (11), the integral acquires an imaginary part only if $\omega \geq k_f^2/(2\mu)$. This, however, does not happen for the densities considered here ($\rho \leq 2\rho_0$).

While the decay of the $\Lambda(1405)$ is inhibited by the nuclear medium even above threshold, the shift of its energy/mass changes the real part of the K^-p -scattering amplitude. Once the $\Lambda(1405)$ has moved above threshold, the real part changes sign giving rise to an attractive potential for a low energy K^- in nuclear matter. Finally notice that the cutoff dependence of the results again is very small.

In this simple one channel model it is easy to include effects of finite temperature, which are relevant for the physics of relativistic heavy ion collisions. This is done by replacing the Theta-function $\Theta(k_f - p)$ with the fermi distribution function in the integral of eq. (11). The resulting eigenvalues are plotted in fig. 2 (dashed-dotted line) for a temperature of $T = 150$ MeV. We find that the shift of the mass is smaller than in the zero temperature case, simply because at finite temperature the Pauli-blocking of the low momentum states is less efficient. Furthermore, once the $\Lambda(1405)$ has reached the K^-N threshold, its decay is not entirely Pauli-blocked and, hence, the eigenvalue picks up an imaginary part. This is the reason why we have plotted the dashed-dotted curve only up to densities of $\rho \simeq 1.3\rho_0$. Beyond that value, the eigenvalue is complex. Although the shift in mass at finite temperature is reduced it is still sufficient to warrant an attractive optical potential for a s-wave K^- in a fireball of this temperature.

In order to study the density dependence of the K^- optical potential more quantitatively, we have to evaluate the full K^-p T-matrix, including the coupling to the $\pi\Sigma$, channel in the nuclear medium. This is done by evaluating the T-matrix according to eq. (6) with $g_1(E, k_f)$ given by eq. (10). In fig. 3 we show the real and imaginary part of the $I = 0$ K^-p scattering amplitude as a function of the energy for the free case (full line) as well as for densities $\rho = 0.5\rho_0$, $\rho = \rho_0$, and $\rho = 2\rho_0$. A cutoff of $\Lambda = 1$ GeV has been used. The upward shift of the $\Lambda(1405)$ is clearly visible in the imaginary part of the amplitude and the change in sign of the real part at threshold is nicely demonstrated. Notice, that the width of $\Lambda(1405)$ changes very little, because of the aforementioned blocking of the K^-p decay channel. Also the relative increase in the $\pi\Sigma$ phase space due to the increase in mass of the $\Lambda(1405)$ is small ($\frac{\Delta p}{p} \simeq 0.2$). The long-dashed curve corresponds to the

result obtained for $\rho = 0.5\rho_0$ with a smaller cutoff of $\Lambda = 0.78$ GeV. Again, the cutoff dependence is small.

In order to determine the K^- optical potential in nuclear matter, we have to include the isospin $I = 1$ contribution as well

$$U_{tot} = \frac{1}{4}U_{I=0} + \frac{3}{4}U_{I=1} \quad (12)$$

Since in the energy region of interest there are no resonances which could be affected by the nuclear medium similarly to the $\Lambda(1405)$, we determine the $I = 1$ contribution to the optical potential by the lowest order impulse approximation

$$2m_k U_{I=1}(\rho) = -4\pi(1 + \frac{m_k}{m_N}) a_{I=1} \rho \quad (13)$$

where $a_{I=1} = 0.37 + i 0.6$ fm is the empirical scattering length for the isospin $I = 1$ channel. The $I = 0$ contribution we determine by integrating over the fermi sphere of the nucleons

$$U_{I=0} = -8\pi(1 + \frac{m_k}{m_N}) \int d^3k \Theta(k_f - k) f(\omega = \sqrt{(m_p + m_k)^2 + \frac{k^2 m_k}{m_p}}) \quad (14)$$

taking into account some of the fermi momentum corrections, which we find to be small.

In fig. 4, we have plotted the resulting optical potential as a function of density. We find that the real part turns attractive for densities $\rho \geq 0.25\rho_0$. Also the imaginary part increases with density, but it is still comparable in magnitude to the real part, allowing for a quasiparticle approximation of the kaon. Notice, that our result for the optical potential at $\rho = \rho_0$ of $V \simeq -100 - i 100$ is right between the two different fits from the analysis of kaonic atoms by Friedman et al. [14]. They give a value of $V \simeq -73 - i 109$ MeV for their effective ‘ $t\rho$ ’-fit and $V \simeq -188 - i 73$ MeV for their density dependent potential fit.

It has been shown in ref. [15] and more recently [16], that an attractive real part of the optical potential can be achieved microscopically by requiring that the $\Lambda(1405)$ is subject to an attractive mean field of ~ -10 MeV at nuclear matter density, which is to be compared with a standard value of ~ -60 MeV for the nucleon mean field. Consequently, the $\Lambda(1405)$ is shifted upwards by ~ 50 MeV with respect to the in medium K^-N threshold, and thus provides the necessary attraction, as it is now above the in medium threshold. By looking at fig. 3 we see that our calculation also predicts an upward shift of the $\Lambda(1405)$ of about ~ 50 MeV with respect to the K^-N threshold, in nice agreement with the phenomenological analysis².

²In our calculation we have not taken the mean field for the nucleon into account. Inclusion of mean field potential for the nucleons would essentially shift the nucleon and the $\Lambda(1405)$ by the same amount, leaving, however, their mass difference unchanged.

On the other hand, assuming that the $\Lambda(1405)$ is a genuine three quark state, simple counting of the light quarks would suggest that the mean field potential for the $\Lambda(1405)$, is about $2/3$ of that of the nucleon, leading to a relative shift of ~ 20 MeV of the $\Lambda(1405)$. The analysis of the Kaonic atoms, therefore, may be the first phenomenological hint, that the $\Lambda(1405)$ should indeed be viewed as a K^-p bound state. In the following section we will discuss a more direct way to measure the shift of the $\Lambda(1405)$ in matter and, thus, to experimentally investigate the nature of the $\Lambda(1405)$ state.

4 Possible experimental test

The position of the $\Lambda(1405)$ in matter actually can be measured via the reaction

$$p + \gamma \rightarrow K^+ \Lambda(1405) \quad (15)$$

The missing mass spectrum of the K^+ then has a peak at the mass of the $\Lambda(1405)$. These measurements have already been carried out back in the seventies on a hydrogen target [17].

Here, we propose to carry out these measurements using nuclear targets in order to determine a possible shift of the mass of the $\Lambda(1405)$ in matter. These measurements require a photon beam (tagged photons) of energy $E_\gamma \geq 2$ GeV and, therefore, can be carried out at CEBAF.

If a shift of the $\Lambda(1405)$ of $\Delta M \geq 30$ MeV can be established, it would have at least two interesting implications:

- Since the $\Lambda(1405)$ would then be above the K^-N threshold, an s-wave K^- will feel an *attractive* optical potential in matter by scattering through a intermediate $\Lambda(1405)$ -state. This would be an experimental support for the conjectures about kaon condensation in dense matter [1, 2]. It furthermore would confirm the microscopic model for the K^- optical potential needed to fit the data from kaonic atoms [15, 16]. While the spectroscopy of kaonic atoms measures directly the K^- optical potential, it is mostly sensitive to the low density region in the surface of the nucleus. The experiment discussed here, on the other hand, probes the interior of the nucleus, and thus nuclear matter density, provided the target nucleus is large.

Notice, that these implications are independent of the nature of the $\Lambda(1405)$, in particular they are independent of the model for the $\Lambda(1405)$ used in this article.

- As far as the nature of the $\Lambda(1405)$ is concerned an observed large shift (~ 50 MeV) in its mass would help to answer this question. As already briefly discussed in

section 3, from simple quark counting we expect that a genuine 3-quark state will be shifted by only ~ 20 MeV. Contrary to that, the K^-N bound state, which is subject to Pauli-blocking of the intermediate state, will be shifted by ~ 50 MeV, as discussed in the previous section. This argument can actually be sharpened somewhat. A reasonable estimate on the relative shift of a 3-quark- $\Lambda(1405)$ should be that of the lowest Λ state. From the analysis of the binding energies of Λ -hypernuclei the depth of the mean field potential for the Λ has been extracted to be $V_\Lambda = -28$ MeV [18] implying an upward shift of $\sim 20 - 30$ MeV with respect to the nucleon. Furthermore, the same measurement as described here, can also be done for the Λ and have already been proposed in the literature (see e.g. [19]). On the theoretical side, the prediction of the shift of the K^-N can be improved by carrying out a selfconsistent Brueckner-Hartree-Fock type calculation based on a more realistic model for the K^-N interaction.

Using a nuclear target the signal may be distorted through fermi momentum corrections, rescattering of the K^+ , the cross section of which, however, is small, and because of the nuclear surface, where the density and, thus, the shift of the $\Lambda(1405)$ is small. To estimate these corrections, we have performed a Monte Carlo calculation, which takes all these effects into account. We have assumed that the matrix element for the process $\gamma + p \rightarrow K^+\Lambda(1405)$ is independent of energy and isotropic in the c.m. frame. For the mass distribution of the $\Lambda(1405)$ we have chosen a standard Breit Wigner Form. For the rescattering of the K^+ in the nuclear medium we have assumed a cross section of 10 mb. The resulting invariant mass distribution is shown in fig. 5. The full histogram shows the spectrum assuming no changes in mass and in the width of the $\Lambda(1405)$ while the dashed histogram shows the resulting spectrum assuming a mass shift of 30 MeV and an increase of the width by 10 MeV. The shift in the spectrum is still clearly visible and we conclude that in spite of the corrections discussed above a mass shift of $\Delta M \geq 30$ MeV can be observed in this type of experiment³.

5 Conclusions

In this article we have investigated the properties of the $\Lambda(1405)$ resonance in the nuclear medium and its consequences for s-wave K^- -nucleon scattering. Assuming that the

³Notice, that this experiment is sensitive to the mass *difference* between the $\Lambda(1405)$ and the proton and not to the absolute position of the $\Lambda(1405)$. Therefore, an overall shift of the same magnitude for both, the nucleon and the $\Lambda(1405)$, due to the nuclear mean field, which we have not taken into account in our calculation, does not change the outcome of the experiment. Consequently the effect of the Pauli-principle and its implications for the nature of the $\Lambda(1405)$, can be observed in experiment, provided that the *relative* position of the $\Lambda(1405)$ with respect to the nucleon has changed in the medium compared to the free case.

$\Lambda(1405)$ is a K^-p bound state, we could show that its mass increases with density as a result of the Pauli blocking of its wavefunctions. As a consequence, the K^-N s-wave scattering amplitude turns attractive at densities $\rho \geq 0.25\rho_0$ in agreement with the analysis of kaonic atoms. Our findings also support conjectures concerning a possible K^- condensation in dense matter.

The resulting values for the K^- optical potential are of comparable size with the numbers extracted from a fit to kaonic atoms by Friedman et al. [14]. The shift of the $\Lambda(1405)$ -resonance with respect to the KN -threshold is in agreement with that needed in microscopic models for the optical potential of kaonic atoms [15, 16]. In particular, our model provides a dynamical explanation for this shift, which is based on the Pauli blocking of the K^-p wavefunction and, thus, on the compound nature of the $\Lambda(1405)$.

We finally have proposed an experimental check for the shift of the $\Lambda(1405)$, which should be feasible at CEBAF. If a shift larger than ~ 30 MeV could be established, an independent support for an attractive K^- optical potential would be given, with all its implications for astrophysics and the physics of kaonic atoms. Furthermore, these experiments would also help to address the question about the nature of the $\Lambda(1405)$.

We have also briefly discussed the behavior of the $\Lambda(1405)$ at temperatures relevant for relativistic heavy ion collisions. In a simplified model, we found that the mass $\Lambda(1405)$ also increases, again giving rise to an attractive optical potential for the K^- . Such an attractive mean field would be very helpful in order to explain measured kaon spectra at the AGS [6]. One might also wonder, to which extent the now possible decay of the $\Lambda(1405)$ into K^- and proton contributes to the recently observed very cold component in the K^- spectrum [20]. We believe that the contribution is too small, because with a mass of the $\Lambda(1405)$ just above threshold, the branching ratio into K^-p is very small. In addition, the mass of the $\Lambda(1405)$ is fairly high, so that very few $\Lambda(1405)$ will be produced. Thus, it seems very unlikely that enough K^- will come from the $\Lambda(1405)$ to account for the measured enhancement. Furthermore, if the reported slope parameter of ~ 15 MeV is correct, the $\Lambda(1405)$ has to have a temperature as low as ~ 50 MeV, which is to be compared to the canonical value of ~ 150 MeV seen in all other particle spectra.

The natural extension of this work is to include the mean field potential of the nucleon and the K^- in a selfconsistent way along the lines of the Brueckner Hartree Fock scheme and to carry out the full coupled channel problem also at finite temperature. Such a calculation should be based on a realistic interaction for the relevant channels such as e.g. the Jülich approach. A detailed comparison with data from an experiment as proposed above will then provide extremely interesting insight into the nature of the $\Lambda(1405)$ and the properties of a K^- in dense matter.

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Figure captions

Figure 1: Comparison of the results for the forward $I = 0$ scattering amplitude with the analysis of Martin [8].

Figure 2: Mass of the $\Lambda(1405)$ as function of density for the one channel model (eq. (11)).

Figure 3: Forward $I = 0$ scattering amplitude at finite densities for a cutoff of $\Lambda = 1$ GeV. The long dashed corresponds to the result at $\rho = 0.5\rho_0$ for a cutoff of $\Lambda = 0.78$ GeV. The arrow indicates the K^-N threshold.

Figure 4: Resulting optical potential for an s-wave K^- in matter.

Figure 5: K^+ missing mass spectrum for unshifted $\Lambda(1405)$ (full histogram) and for a $\Lambda(1405)$ shifted in mass by 30 MeV at nuclear matter density.

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